COMPONENT PART NOTICE

THIS PAPER IS A COMPONENT PART OF THE FOLLOWING COMPILATION REPORT:

(TITLE): The Effect of the Ionosphere on Radiowave Signals and Systems Performance Based on Ionospheric Effects Symposium Held on 1-3 May 1990.

(SOURCE): Naval Research Lab., Washington, DC

TO ORDER THE COMPLETE COMPILATION REPORT USE AD-A233 797.

THE COMPONENT PART IS PROVIDED HERE TO ALLOW USERS ACCESS TO INDIVIDUALLY AUTHORED SECTIONS OF PROCEEDINGS, ANNALS, SYMPOSIA, ETC. HOWEVER, THE COMPONENT SHOULD BE CONSIDERED WITHIN THE CONTEXT OF THE OVERALL COMPILATION REPORT AND NOT AS A STAND-ALONE TECHNICAL REPORT.

THE FOLLOWING COMPONENT PART NUMBERS COMPRISE THE COMPILATION REPORT:

AD#: TITLE:

AD-P006 265 thru AD-P006 325

Accesion For	
NTIS CRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and / or Special
A-1	

IONOSPHERIC ERRORS AT L-BAND FOR SATELLITE AND RE-ENTRY OBJECT TRACKING IN THE EQUATORIAL ANOMALY REGION

W. A. Pakula
Cadet Squadron 33
USAF Academy, Colorado 80841

J.A. Klobuchar and D. N. Anderson
Ionospheric Physics Division
Hanscom AFB, MA 01731

P. H. Doherty
Institute for Space Research
Boston College
Newton, MA 02159

ABSTRACT

The ionosphere can significantly limit the accuracy of precise tracking of satellites and re-entry objects, especially in the equatorial anomaly region of the world where the electron density is the highest. To determine typical changes induced by the ionosphere, the Fully Analytic Ionospheric Model, (FAIM), was used to model range and range-rate errors over Kwajalein Island, located near the equatorial anomaly region in the Pacific. Model results show that range-rate errors of up to one foot per second can occur at L-band for certain, near-vertical re-entry object trajectories during high solar activity daytime conditions.

Since the variability of the location and strength of the equatorial anomaly peak electron density region is large, models which fail to take into account the actual position of the anomaly, at the time when the space object is being tracked, can result in erroneous range and range-rate corrections. Even relatively small velocity errors can be significant if they have the cumulative effect of producing large total range errors over the entire space object flight path.

INTRODUCTION

The purpose of this investigation was to model the effects the ionosphere can have on precise tracking of a satellite by an L band radar, as well as the effects on tracking a re-entry object, either being tracked by a radar, or carrying an L-band transponder, in producing target range and velocity errors. In order to demonstrate "worst case" conditions the equatorial anomaly region of the world was chosen because the highest electron densities in the world occur in this region. The equatorial anomaly produces the world's highest ionospheric electron densities in regions displaced approximately plus and minus 15° either side of the earth's magnetic equator, due to an electric field at the magnetic equator which moves ionization upwards at the equator, then across magnetic field lines to the anomaly latitudes. Since Kwajalein Island is located nearly under the equatorial anomaly it was chosen as a representative location to study the effects of ionospheric range and range-rate errors on precise tracking of re-entry objects. The ionospheric model used was the Fully Analytic Ionospheric Model, FAIM, developed by Anderson, et. al., (1989), which does a realistic job of representing the low latitude F region for various seasonal and solar cycle activity conditions.

IONOSPHERIC RANGE AND RANGE-RATE ERRORS

The additional time delay, over the free space transit time, of a signal transmitted from above the ionosphere to a user on, or near, the earth's surface was given by Millman (1965) and can be expressed as:

$$(\text{Delta})\ t = \frac{40.3}{c * f^2} * \text{TEC} \qquad (\text{seconds}) \qquad (1).$$

where TEC is the total number of electrons along the path from the radar to the target, c is the velocity of light in meters/second, and f is the system operating frequency in Hertz. The TEC is generally expressed as the number of electrons in a unit cross section column of one square meter area along the radar signal path.

For a radio or radar signal at 1.6 GHz, a TEC value of 10^{18}, a value commonly exceeded in the equatorial anomaly region, would produce a one-way range error due to the ionosphere of 15.7 meters, or 51.6 feet.

The one way error in range-rate, or velocity, which the ionosphere produces on radio or radar signals can be expressed as:

$$\text{Delta (phi)} = \frac{1.34 \times 10^{-7}}{f} * \text{TEC} \qquad (\text{cycles}) \qquad (2).$$

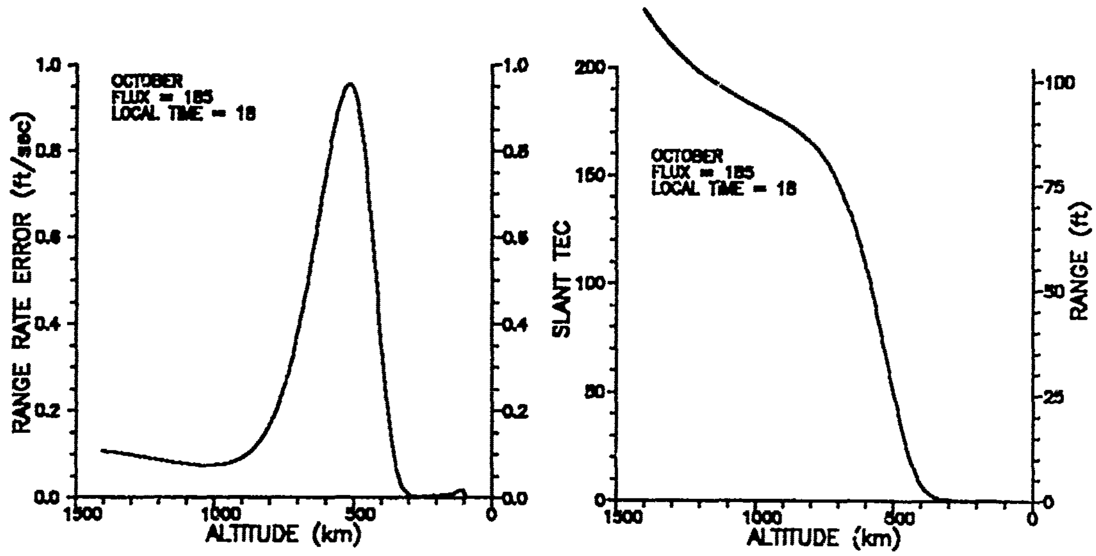
where Delta (phi) is the number of RF carrier cycles of phase path decrease suffered by the signal. At 1.6 GHz, one cycle, (wavelength), corresponds to 0.62 feet of distance, and for a rate of change of TEC of 10^{16} el/m^2 per second, the range-rate, or velocity, error would be 0.52 feet per second. If that rate of change continued for 30 seconds, the cumulative range error would be 4.76 meters or 15.6 feet.

Range-rate errors are produced by the rate of change of the TEC over the radio or radar target velocity measurement interval. Since this measurement interval can be as short as one second, the change in TEC over a one second interval is the important parameter in computing ionospheric range-rate errors. The change in TEC, looking in a fixed direction, normally does not change rapidly, since only the slow diurnal changes in TEC are involved. However, a radar tracking a space object, especially an object re-entering the atmosphere, can see relatively large changes in TEC along the target trajectory, especially as it goes through the region of ionospheric peak electron density. Thus, the effective rate of change of TEC which the radar sees, over its velocity tracking interval, is the important parameter, in range-rate calculations, and not the absolute value of TEC itself.

RANGE AND RANGE-RATE CALCULATIONS FOR A RE-ENTRY OBJECT

Since the operating frequency of the tracking system is known, the fundamental problem becomes one of calculating the ionospheric TEC along a Line Of Sight (LOS) from the transmitter to the re-entry object. Mathematically, this is equivalent to integrating an electron number density function (electrons per cubic meter) over a certain path (meters) to get units of electrons per square meter. Rates of change were then calculated by the difference of TEC over successive one second intervals as the re-entry object moved downwards through the ionosphere.

First, an orbital generation program was used to determine a typical trajectory of a re-entry object. The prepared input file contained the geographic latitude, longitude, and altitude of the re-entry object for each second of a typical flight path following apogee. It also contained the x, y, z, Earth-Centered, Earth-Fixed (ECEF) coordinates of the re-entry object for the same times. The ECEF system is simply that right handed, orthogonal coordinate system with the x-axis pointing towards the Greenwich meridian and the z-axis pointing towards the north geographic pole. The other coordinate systems used in the program are geographic and geomagnetic Local Level (LL) coordinates. LL

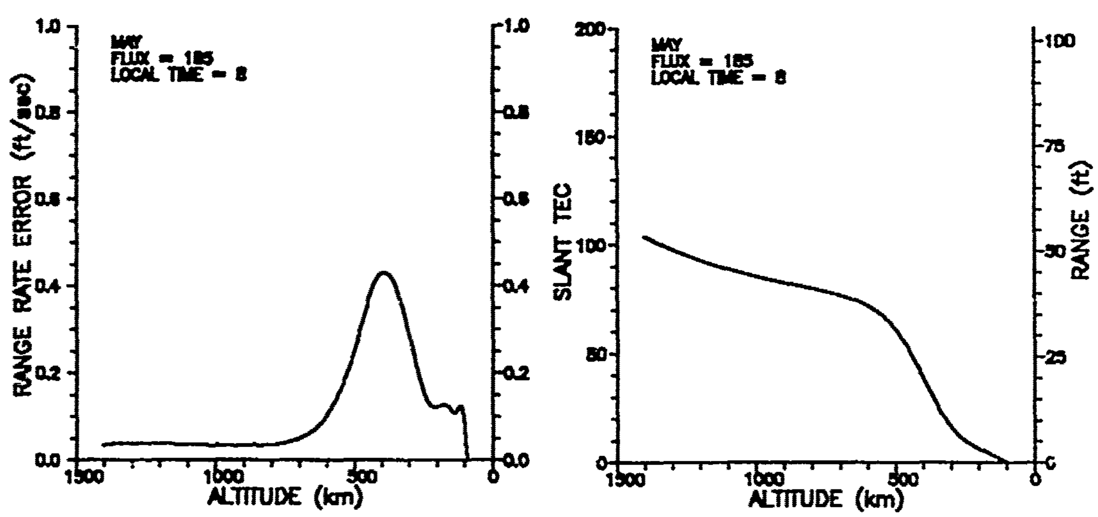


a) Range-rate error versus altitude for October, solar flux = 185, 18 hours local time.

b) Range error versus altitude for October, solar flux = 185, 18 hours local time.

FIGURE 1.

For the month of May, for the same solar flux, but at 0800 local time, when the TEC is much lower, the maximum range-rate error is 0.430 feet per second and occurs at an altitude of 394 kilometers, as illustrated in Figure 2A. The corresponding slant TEC, corresponding to radar range error as a function of re-entry object height is shown in Figure 2B.

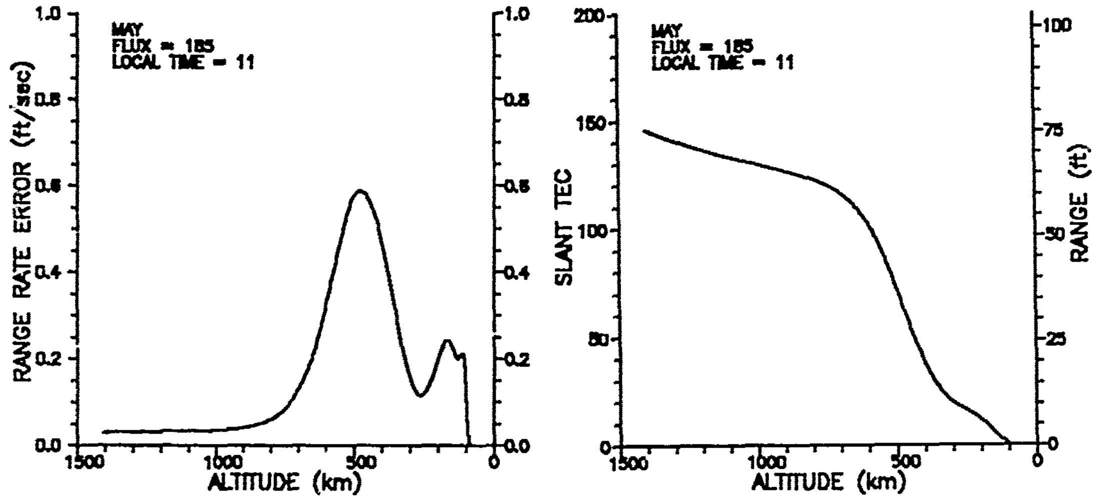


a) Range-rate error versus altitude for May, solar flux = 185, 08 hours local time.

b) Range error versus altitude for May, solar flux = 185, 08 hours local time.

FIGURE 2.

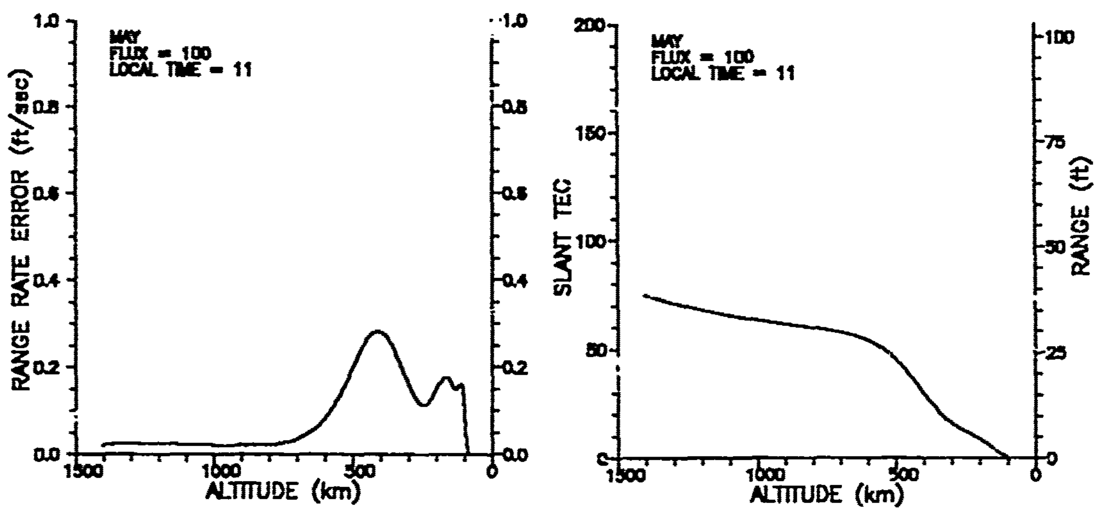
For the same conditions as those in Figure 2, namely May, with a solar flux of 185, but at 1100 hours local time, the maximum range-rate is 0.587 feet per second which occurs at an altitude of 476 km. The range-rate and TEC for this case as shown in Figures 3A and 3B respectively. To contrast this case against one with a low value of solar flux, Figures 4A and 4B illustrate the range-rate and slant TEC, respectively, for May at 1100 hours local time, but with a solar flux of 100. The largest range-rate error for this case was 0.282 feet per second.



a) Range-rate error versus altitude for May, solar flux = 185, 11 hours local time.

b) Range error versus altitude for May, solar flux = 185, 11 hours local time.

FIGURE 3.



a) Range-rate error versus altitude for May, solar flux = 100, 11 hours local time.

b) Range error versus altitude fcr May, solar flux = 185, 11 hours local time.

Figure 4.

coordinates consist of latitude, longitude, and altitude. Once the input file was prepared, the actual velocity error calculations were made. All test cases used Kwajalein Island as the simulated tracking site, due to its location nearly under the equatorial anomaly.

Second, the ECEF coordinates of forty points along the direct LOS from the tracking station to the first point in the re-entry object trajectory were calculated by means of an iterative loop. Each coordinate triplet was also converted, within the loop, to geographic LL coordinates. As each LOS point was calculated, the Local Time (LT) for each point was determined by finding the difference in longitude between the LOS point and the splashdown point of the re-entry object, and adding/subtracting the equivalent number of hours to the splashdown time. Once the LOS coordinate array and corresponding LT array were filled for all forty points, the entire LOS array was converted from geographic to geomagnetic LL coordinates.

Next, the electron number densities at each point in the LOS array were found through repeated calls to the FAIM model ionospheric code. Important inputs to FAIM consist of the geomagnetic LL coordinates and the LT for the point and time of interest, the current month, and solar flux. The model then returns the number electron density for the given point and the specified conditions. FAIM was used to calculate the electron density for each of the forty points along the LOS. These number densities were then integrated along the LOS, resulting in the TEC of the ionosphere from the tracking station to the re-entry object. This overall process of finding the TEC was repeated for each LOS, one per each second of flight time, from apogee to splashdown.

Once the TECs along each slanted LOS were known, the phase advance of the tracking signal for each point in the trajectory were easily found using equation (2). Using a curve fitting package, a phase advance versus re-entry object flight time was constructed. Finally, the derivative of this curve was calculated for each point in the re-entry object trajectory. These were used in accordance with (2) to calculate the range- rate errors produced at each point in the trajectory. To simplify the calculations the location of the re-entry object splashdown and the ground radar were assumed to be coincident, though small differences in these locations do not significantly change the results.

Among the assumptions made by the program are the following:

- spherical earth coordinate transformation from ECEF to LL coordinate system

- splashdown location and radar location are the same

- the approx. 6 minute travel time of RV is negligible in inputting time to FAIM model, that is any diurnal changes in electron density were small during that time interval

- electron number density is set to zero below 50 kilometers re-entry object altitude

- solar flux activity levels greater than 185 are not accepted by FAIM, and are thus not used

RESULTS

Ten test cases were run for different seasons, solar activity and local times of day. The maximum range-rate error for all the test cases was for October at 18:00 hours Kwajalein time, with a solar 10.7 cm. flux of 185. For those conditions the ground radar will experience a maximum range-rate error of -0.955 feet per second, at the point when the re-entry object is at an altitude of 516 kilometers. This is shown in Figure 1A, along with the corresponding slant TEC curve on Figure 1B.

In all test cases the maximum range rate errors were produced when the slant TEC curves had the greatest slope, or first derivative. This was to be expected, since the range rate error equation includes the first derivative of the phase advance, which is dependent upon the TEC. This can be seen by referring, for example, to figures 1A and 1B. Note that the maximum range-rate error, in Figure 1A, occurs at the point, in Figure 1B, where the rate of change of TEC is greatest. Thus, in the case of an object traveling rapidly through the ionosphere, it is the rate of change of TEC, and not the TEC itself, which dictates the magnitude of the range-rate error. Table 1 summarizes the maximum range rate errors calculated for all test cases, along with the altitude at which they occur.

TABLE 1.

Case	Month	Flux	Time (hrs)	....MAXIMUM ERROR.... Range (ft)	Range Rate (ft/sec)	Altitude (km)
1	MAY	185	11	75	-0.59	476
2	MAY	185	8	54	-0.43	394
3	OCT	185	11	106	-0.87	440
4	MAY	100	11	39	-0.28	412
5	OCT	185	18	117	-0.96	516
6	JAN	185	11	72	-0.68	339
7	JAN	100	11	38	-0.38	287
8	MAR	185	11	101	-0.82	434
9	MAR	185	6	18	-0.197	307
10	MAY	185	14	101	-0.798	480

Table 1: Maximum range and range-rate errors. The maximum range error occurs when the object is at its greatest range. The maximum range-rate error occurs at the altitude indicated.

CONCLUSIONS

The range and range-rate errors produced by the ionosphere on an L-band radar or tracking beacon can be significant if precision tracking is required. Analysis of the problem using the FAIM ionospheric model predicts range-rate errors to be on the order of 1/2 to 1 foot per second for the conditions used in this study. Due to the limitations of the FAIM model solar flux values only up to 180 could be used, however, the smooth 10.7 cm. solar flux for the present solar cycle maximum is approximately 250. The values for ionospheric range and range-rate error presented here are certainly lower than those which would be encountered during the present solar maximum conditions.

REFERENCES

Anderson, D. N., J. M. Forbes, and M. Codrescu, "A Fully Analytic, Low-and Middle-Latitude Ionospheric Model", J. Geophys. Res., V. 94, No. A2, pp 1520-1524, Feb. 1, 1989.

Millman G. H. in Modern Radar, Edited by R. S. Berkowitz, John Wiley & Sons, New York, (1965).